



LED Color Stability: 10 Important Questions

DOE Webinar

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10 Important Questions

1. Why and where is color stability important?
2. What metrics are used to describe color shift/color stability?
3. When does color shift become noticeable?
4. Are there established tolerances for color shift?
5. What standards apply to the measurement of color shift?
6. To what types of products do color stability measurement standards apply?
7. What causes color shift?
8. Are there methods and/or standards for projecting color shift in the future using measured data?
9. Are warranties that cover color shift available?
10. How should end users and/or specifiers monitor color over time?

1. Why and where is color stability important?

- **Color Shift/Color Stability:** Comparison of spectral power distributions over time
 - Many types of lamps emit light differently depending on the operating condition (ambient air temperature, for example). Sometimes these changes are recoverable.
 - For some lamps or luminaires, the materials or construction may change over time, resulting in changes to the spectral output.
 - Color shift is generally independent of lumen depreciation, although they can be related.
- **Color Consistency:** Comparison of initial spectral power distributions for a group of matching lamps or luminaires
 - Color consistency over time is also different from color stability.

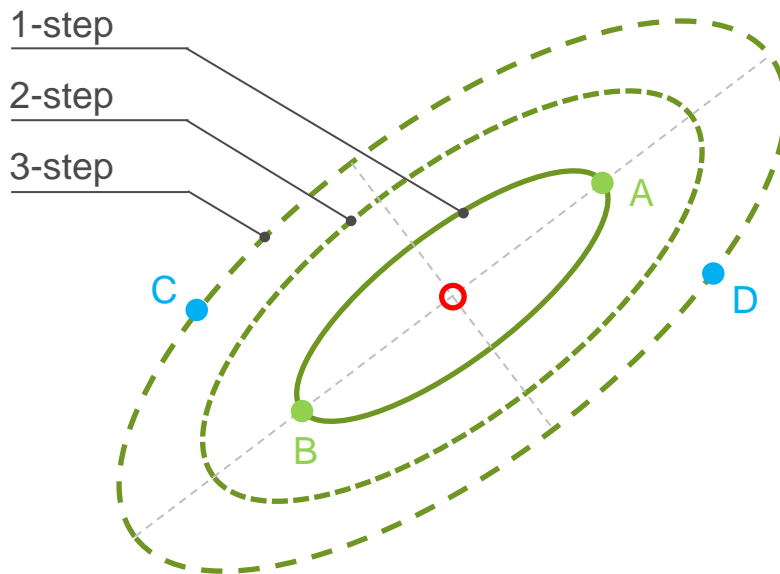
1. Why and where is color stability important?

- To meet lifetime claims, performance expectations must be met the whole time
- Color shift can be a problem anywhere appearance is important: museums, retail, residences, wall washing, façade lighting, coves, direct view
- Color stability is less important in areas like roadways, parking lots, utility spaces



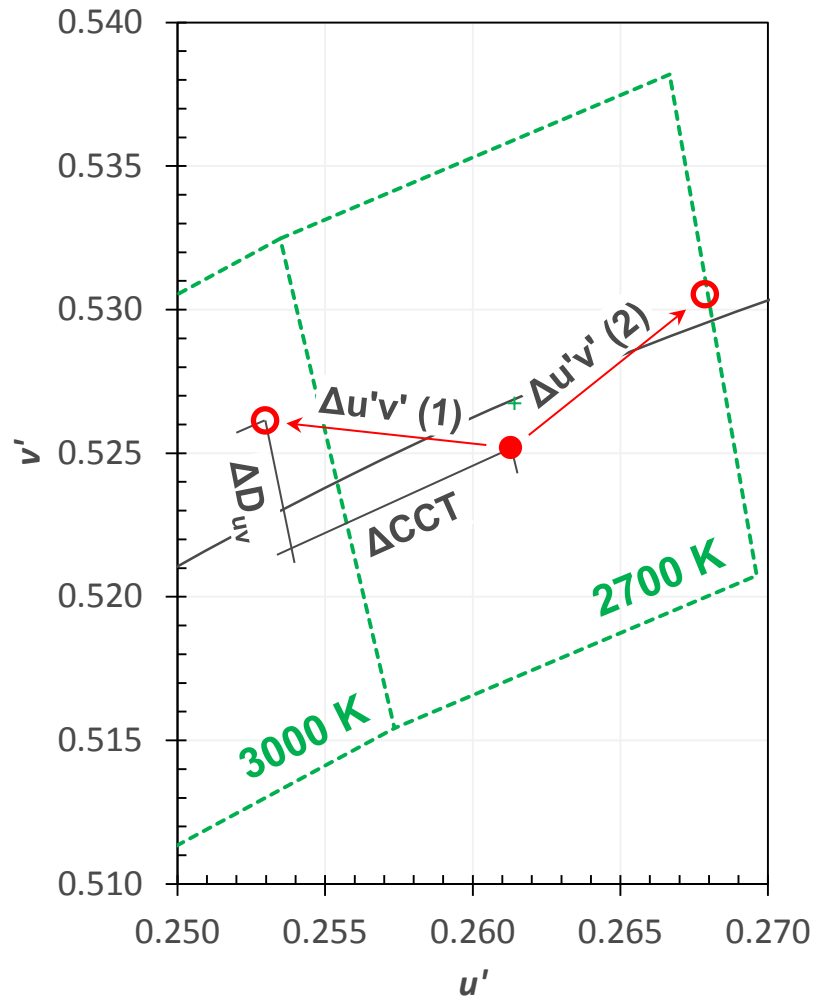
2. What metrics are used to describe color shift/color stability?

MacAdam Ellipses



- Experimentally-derived indicators of human color vision tolerances at various chromaticities
- Based on the observations of one highly-trained observer in a very specific scenario/apparatus; results cannot be translated to every installation
- Sometimes referred to as SDCM (standard deviation of color matching)
- Can be reported in multiples (e.g., 3-step ellipse)
- Do not convey the direction of shift/difference

2. What metrics are used to describe color shift/color stability?

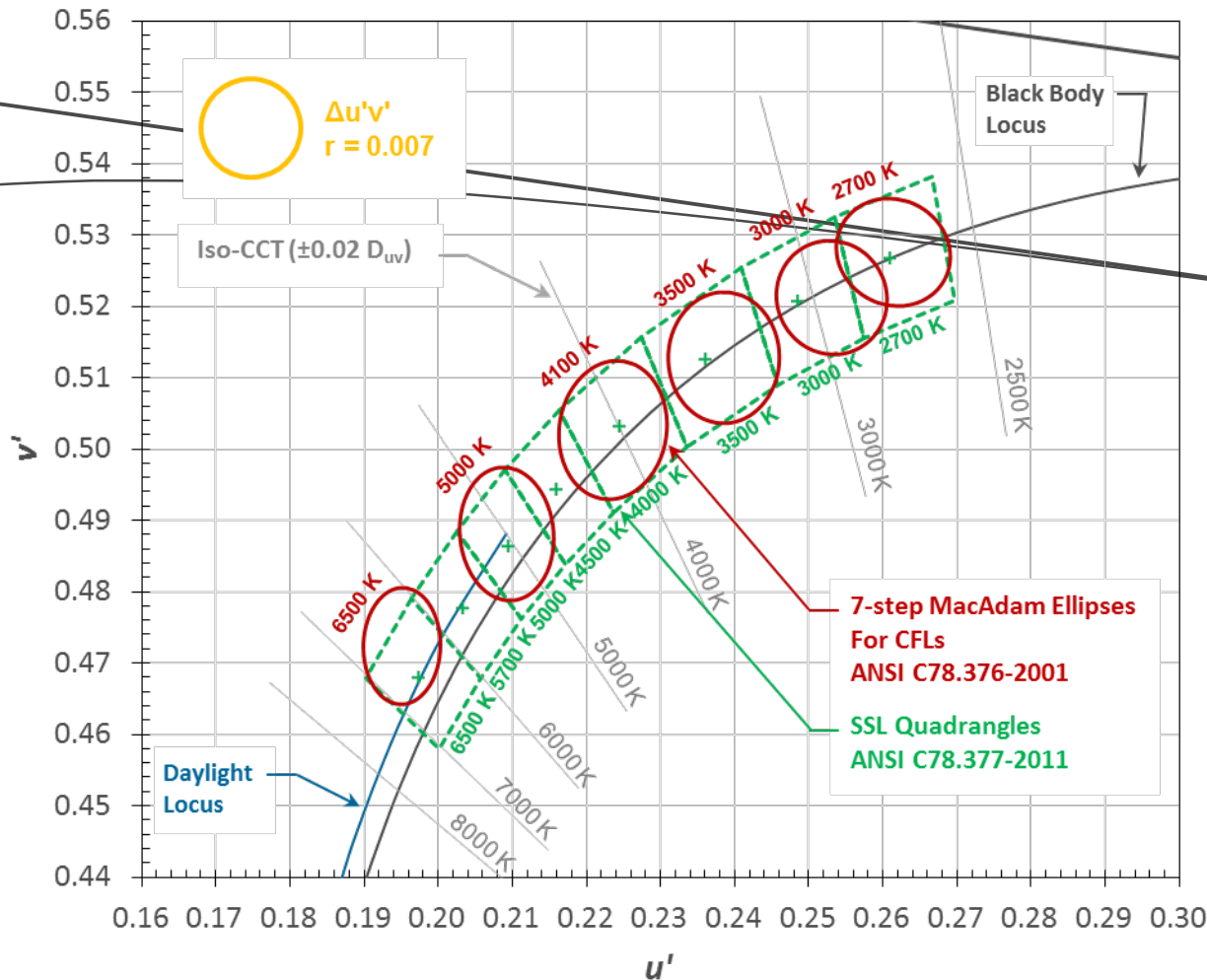


$\Delta u'v'$

- $\Delta u'v'$ is the Euclidian distance between two sets of chromaticity coordinates in the CIE 1976 UCS chromaticity diagram.
- As with MacAdam Ellipses, $\Delta u'v'$ does not convey the direction of a shift
- $\Delta u'v'$ does not convey whether or not a difference is noticeable

2. What metrics are used to describe color shift/color stability?

$\Delta u'v'$ and MacAdam Ellipses



- MacAdam ellipses are approximately circles in the 1976 (u' , v') chromaticity diagram
- A 1-step ellipse is approximately equal to a $\Delta u'v'$ of 0.001
- ANSI definitions of white light allow for fairly large tolerances (~14-step difference from edge to edge)

3. When does color shift become noticeable?

The million dollar question...

It depends.

Viewer

Field of View

Surface Characteristics

Proximity

Time

In MacAdam's experimental setup, a just noticeable difference was determined to be three times the standard deviation of color matching (or a 3-step ellipse) for a given observer. However, a 1-step ellipse is often called a *MacAdam unit of color difference*.

4. Are there established tolerances for color shift?

- **ENERGY STAR:** Lamp change in chromaticity from 0-hour measurement, at any measurement point during the first 6,000 hours of lamp operation, shall be within a total distance of 0.007 on the CIE 1976 u'v' diagram. Nine or more units shall meet the requirement.

http://www.energystar.gov/ia/partners/product_specs/program_reqs/ENERGY_STAR_Lamps_V1_Final_Specification.pdf?5c9d-0f85

- **LRC Assist:** 2-Step or 4-Step ellipse *for LED binning* depending on the application.

<http://www.lrc.rpi.edu/programs/solidstate/assist/pdf/colordiscriminationstudy.pdf>

- **Lacking better standards, tolerances must be established on a case-by-case basis.**

5. What standards apply to the measurement of color shift?

- At the device (LED) level IES LM-80-xx (Approved Method: Measuring Lumen Maintenance of LED Light Sources) supports the measurement and reporting of color shift over time
 - Colorimetric values are measured from the total spectral radiant flux of the individual LED package every 1000 hours (min)
 - LEDs are subjected to a predefined set of temperatures and drive currents
 - The chromaticity is then measured at a fixed ambient temp (25° Celsius)
 - The chromaticity shift across the total test duration (6,000K hours min) is included in the LM-80 report

Delta u'v' for If = 700mA (L1T2-4085000000000)

		0hrs	24hrs	168hrs	500hrs	1000hrs	2000hrs	3000hrs	4000hrs	5000hrs	6000hrs	7000hrs	8000hrs	9000hrs	10000hrs
DATASET 55 Ts=Tair=120°C	median =	0.0000	0.0001	0.0002	0.0003	0.0005	0.0018	0.0020	0.0020	0.0025	0.0035	0.0049	0.0059	0.0061	0.0059
	average =	0.0000	0.0001	0.0003	0.0003	0.0006	0.0018	0.0020	0.0020	0.0027	0.0035	0.0050	0.0059	0.0063	0.0060
	st dev =	0.0000	0.0001	0.0003	0.0002	0.0004	0.0004	0.0006	0.0005	0.0010	0.0008	0.0007	0.0009	0.0009	0.0010
	min =	0.0000	0.0000	0.0001	0.0000	0.0001	0.0010	0.0013	0.0013	0.0016	0.0025	0.0040	0.0043	0.0047	0.0045
	max =	0.0000	0.0002	0.0010	0.0007	0.0015	0.0029	0.0038	0.0036	0.0050	0.0053	0.0065	0.0076	0.0080	0.0080
DATASET 56 Ts=Tair=105°C	median =	0.0000	0.0002	0.0001	0.0005	0.0004	0.0004	0.0004	0.0008	0.0005	0.0004	0.0014	0.0006	0.0006	0.0008
	average =	0.0000	0.0002	0.0003	0.0005	0.0005	0.0006	0.0006	0.0014	0.0007	0.0007	0.0017	0.0008	0.0007	0.0007
	st dev =	0.0000	0.0001	0.0004	0.0003	0.0003	0.0005	0.0005	0.0010	0.0006	0.0006	0.0010	0.0006	0.0005	0.0005
	min =	0.0000	0.0001	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0001	0.0001	0.0001	0.0000	0.0001
	max =	0.0000	0.0003	0.0014	0.0011	0.0013	0.0019	0.0020	0.0041	0.0020	0.0019	0.0041	0.0021	0.0020	0.0022
DATASET 57 Ts=Tair=85°C	median =	0.0000	0.0003	0.0003	0.0007	0.0006	0.0004	0.0004	0.0001	0.0003	0.0004	0.0003	0.0005	0.0005	0.0006
	average =	0.0000	0.0003	0.0003	0.0007	0.0006	0.0005	0.0004	0.0004	0.0004	0.0004	0.0004	0.0005	0.0005	0.0006
	st dev =	0.0000	0.0001	0.0001	0.0003	0.0002	0.0002	0.0003	0.0004	0.0003	0.0003	0.0004	0.0003	0.0003	0.0002
	min =	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0000	0.0001	0.0000	0.0001	0.0000	0.0000	0.0001
	max =	0.0000	0.0004	0.0005	0.0011	0.0008	0.0010	0.0012	0.0015	0.0013	0.0013	0.0015	0.0012	0.0012	0.0010
DATASET 58 Ts=Tair=55°C	median =	0.0000	0.0003	0.0002	0.0008	0.0008	0.0007	0.0003	0.0002	0.0002	0.0004	0.0007	0.0020	0.0020	0.0019
	average =	0.0000	0.0003	0.0003	0.0008	0.0008	0.0007	0.0003	0.0002	0.0003	0.0004	0.0008	0.0021	0.0022	0.0021
	st dev =	0.0000	0.0001	0.0001	0.0002	0.0001	0.0002	0.0001	0.0001	0.0002	0.0002	0.0004	0.0004	0.0004	0.0004
	min =	0.0000	0.0001	0.0001	0.0004	0.0005	0.0002	0.0001	0.0001	0.0001	0.0001	0.0004	0.0014	0.0015	0.0014
	max =	0.0000	0.0004	0.0004	0.0010	0.0010	0.0009	0.0005	0.0007	0.0009	0.0009	0.0018	0.0032	0.0034	0.0032

Summary

Product: LUXEON TX

CCT/CRI: 4000K/85 CRI

I : 700mA

Ts: 55°, 85°, 105°, 120° Celsius

Test Duration: 10,000 hours

Delta u'v': 0.0006-0.0060

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LUMILEDS

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5. What standards apply to the measurement of color shift?

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- What about at the system/luminaire level?...
- IES LM-79-xx? (Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products)
 - Chromaticity (spatially integrated) is measured at a fixed ambient temp (25° Celsius) and time only
 - The LM-79 test report only states the color quantities (chromaticity coordinates, CCT and CRI)

6. To what types of products do color stability measurement standards apply?

- Simple answer... Just the discreet LED package/device
- Begs the question... "Can LED package data be applied to LED lamps and luminaires?"

LED Lamp	LED Luminaire
Designed for lowest price, reasonable life (10K + hours) and comparable photometric performance (vs. traditional lamps)	Designed for moderate price, robust life (25K+ hours) and high photometric performance (vs. traditional sources)
System = LEDs, simplest optics possible, lowest cost driver, minimal thermal management	System = LEDs, comparable optics, driver and thermal management for the application
<i>"Can LED package data be applied to LED lamps and luminaires?"</i>	
<i>Risky</i>	<i>Probably...If you approach it as a SYSTEM</i>
Designed to (or close to) the limits of most of the components	LEDs – LM-80 characterization Optics (Lens, Mixing Chamber, Solder Mask) Thermal management (ambient vs. max temp)

7. What causes color shift?

LED Packages:

Materials and manufacturing methods used in LED package production are known to contribute to color point stability over time. The primary factor that contributes to LED color performance is operating temperature.

Luminaire Construction:

As with LED packages, the materials and methods used to assemble luminaires can affect the color shift of the product. Temperature again is an important factor.

Application:

The environment in which the luminaire is operated can adversely affect the color point stability.

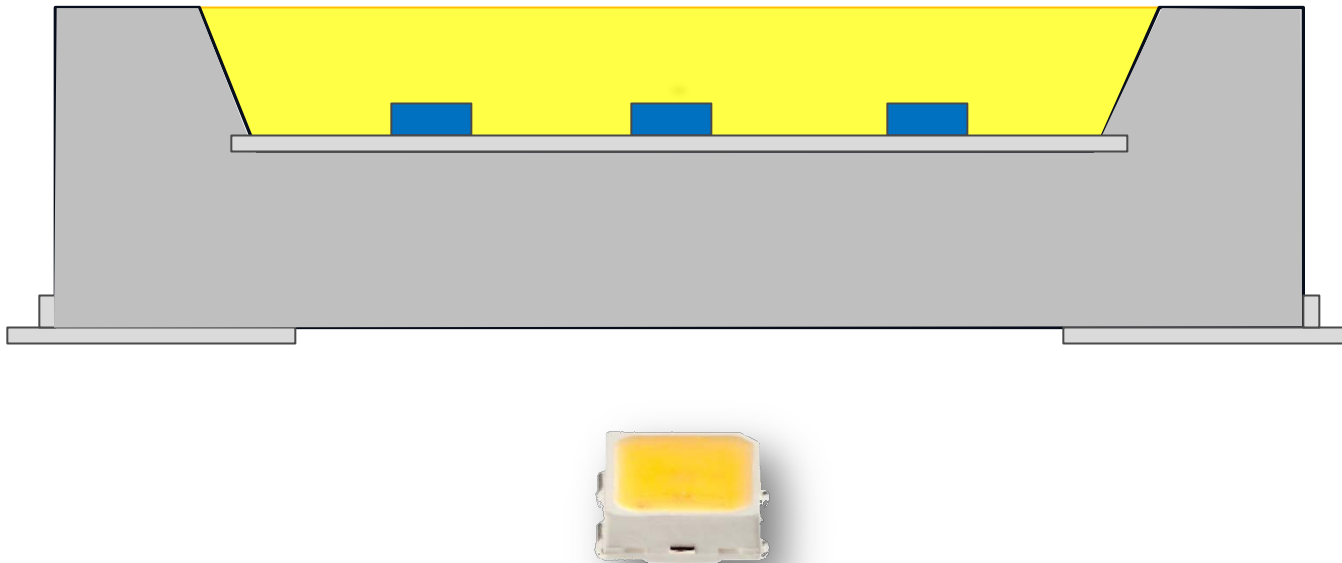
7. What causes color shift?

LED Packages: Plastic Low- and Mid-Power

The white reflective material used in the construction of these LEDs is a synthetic plastic resin called polyphthalamide (abbreviated as PPA).

It is well known that at high temperatures PPA will discolor, which will reduce the light emitted from the LED.

PPA will also discolor when subjected to high energy (low wavelength) photons emitted from blue LEDs.

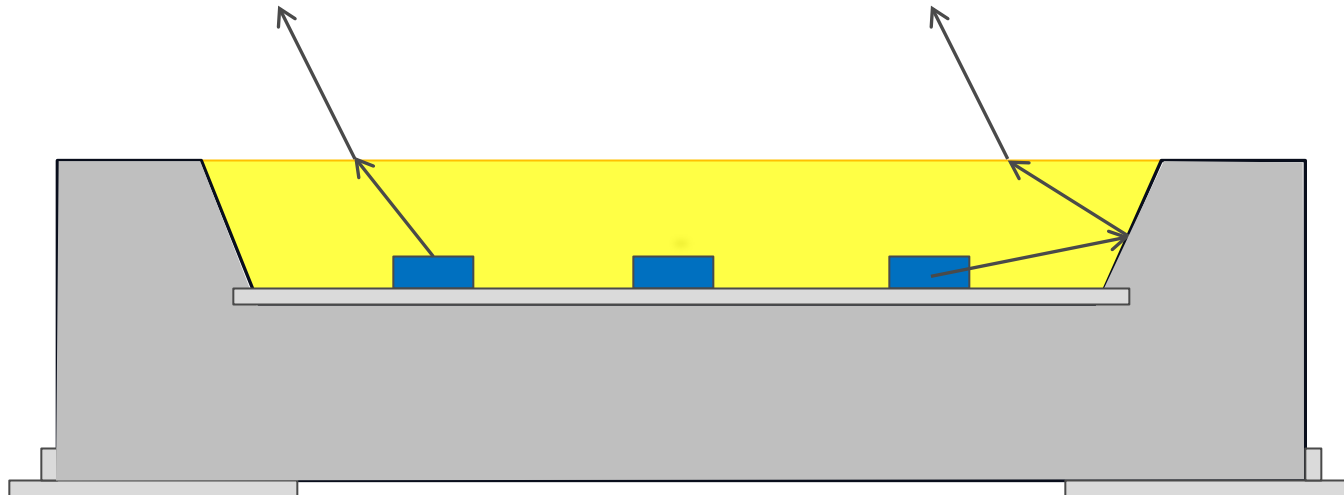


7. What causes color shift?

LED Packages: Plastic Low- and Mid-Power

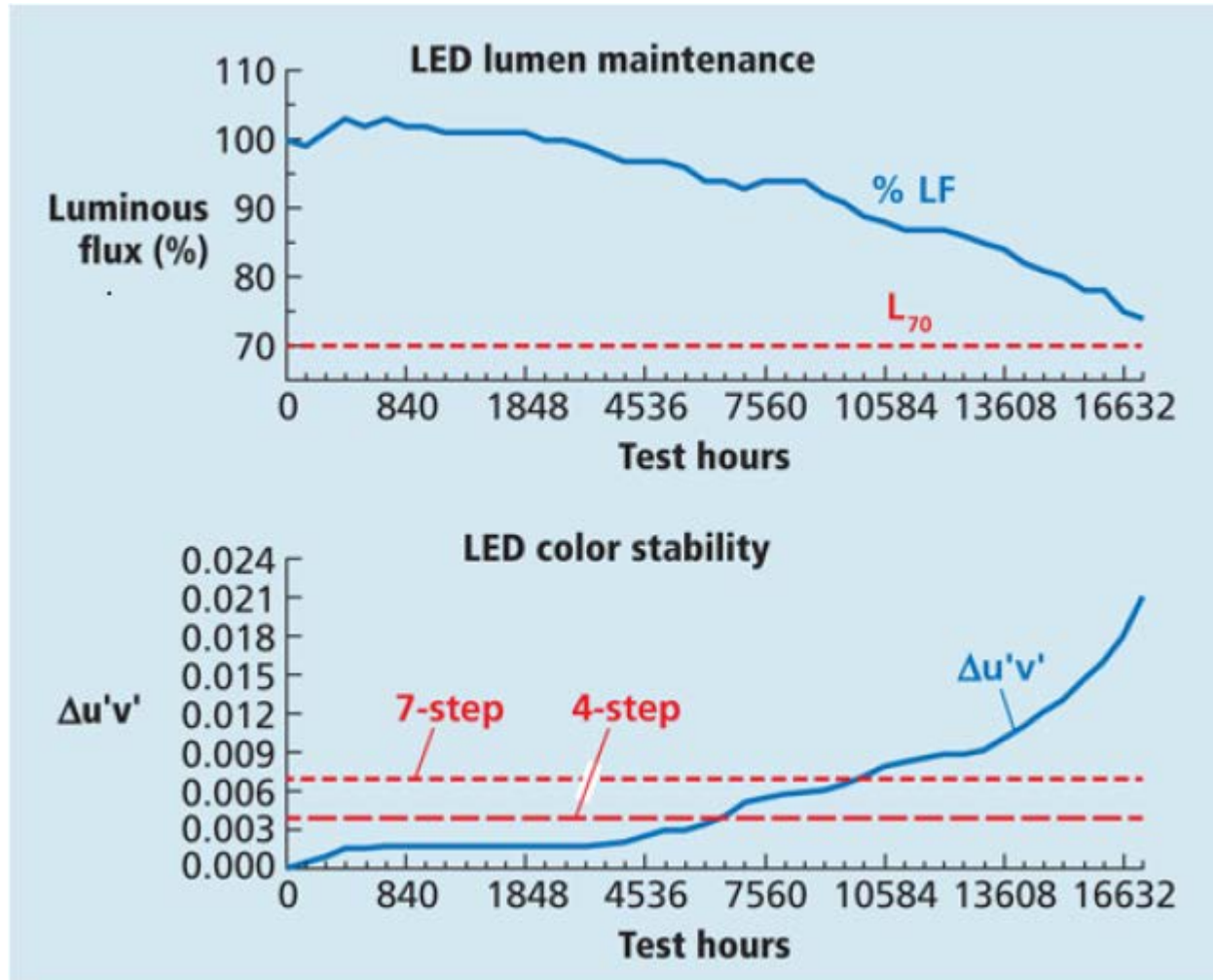
These photons will continue to be emitted from the package since they are not reflected off the walls of the package

These photons will not be reflected off the package walls. So the average path through the phosphor of the emitted photons will decrease. A blue shift in the part will result.



7. What causes color shift?

LED Packages: Plastic Low- and Mid-Power



*From "Understanding the true cost of LED choices in SSL Systems",
Tuttle & McClear, LEDs Magazine, February 2014

7. What causes color shift?

LED Packages: Ceramic High Power, Chip Phosphor Coated

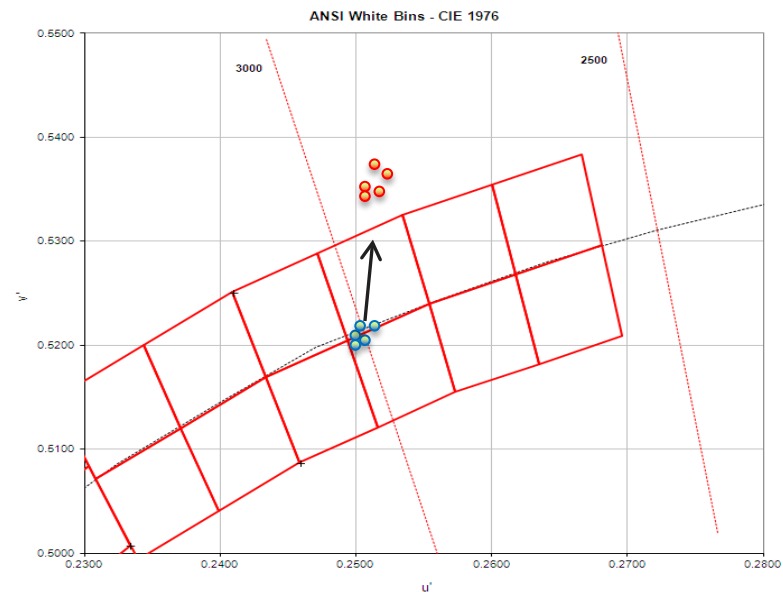
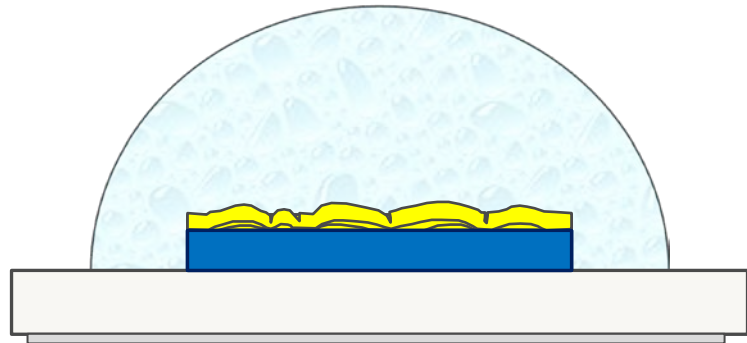
Phosphor is mixed with a “binder” and placed onto top of chip.

The chip and phosphor are encapsulated with a silicone lens.

Over time the phosphor can crack and delaminate from the surface of the LED chip due to stress.

If the cracking and delamination is severe the color will shift warmer and above the black body curve.

The color shift is due to a relative increase in the distance the blue photons travel through the phosphor. The longer distance results in additional down-conversion of the blue photons to longer wavelengths.



7. What causes color shift?

LED Packages: Ceramic High Power, Chip Phosphor Coated

Color shift observed with high power LED packages is temperature dependent. The higher the solder point temperature the faster the shift will occur.

For LEDs with the junction very close to the phosphor coated surface, the higher the junction temperature the faster the shift will occur.

Higher LED drive currents = higher junction temperature. For a given T_{sp} , the higher the drive current the faster the shift will occur.

The temperature of the phosphor particles above the chip also affects the rate of color shift change. The phosphor temperatures are believed to be at least 35°C to 45°C above the junction temperature. So, the efficiency of the phosphors used in the LED package (warm white vs cool white) will play a part in how quickly the color shifts.

7. What causes color shift?

Luminaire Construction – materials can oxidize during operation of product resulting in both a loss of light and color shift.

Reflective Surfaces



Lenses

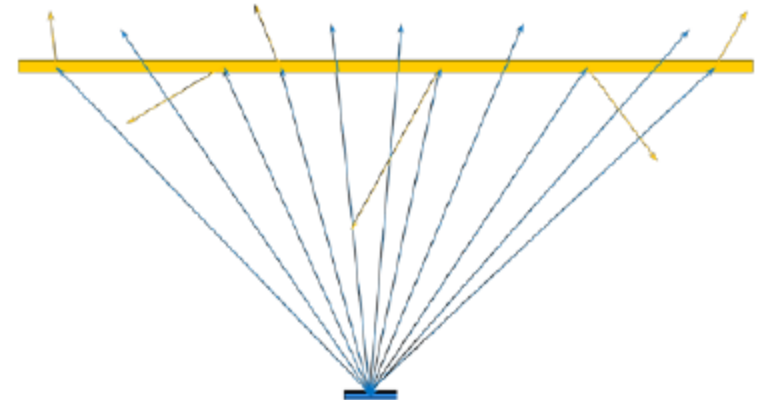
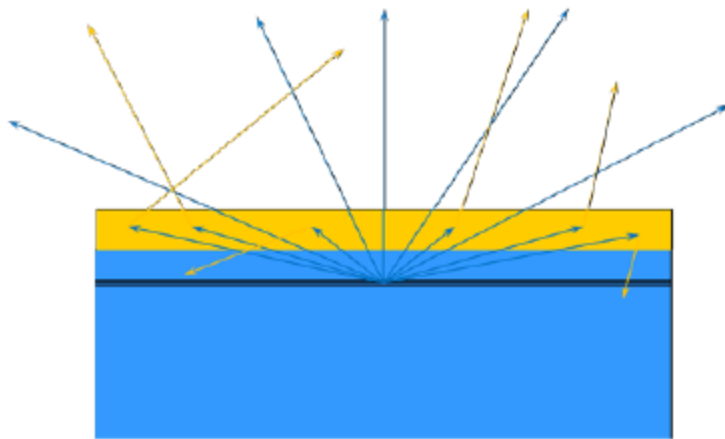


Diffusers



7. What causes color shift?

Luminaire Construction – Remote Phosphor Products



Phosphor Heating due to photonic energy can oxidize the plastic material on which the phosphor has been coated.

7. What causes color shift?

Application Conditions

Contaminants that come into contact with a luminaire during its operation can cause degradation of reflective surfaces in the LED package and luminaire that will accelerate color shift.

Sulfur is a well known example of such a material. It will tarnish highly reflective silver surfaces.

Sulfur is present in the environment around us (i.e. Automobile exhaust fumes).

Other corrosive materials can attack plastics and used in the construction of a luminaire.

8. Projecting Color Shift – LED packages?

LM-80 has recommended testing LEDs at 55° C, 85° C and a third temperature that is left up to the discretion of the LED package manufacturer.

Most LED manufacturers now include 100° C to 105° C as a third test temperature.

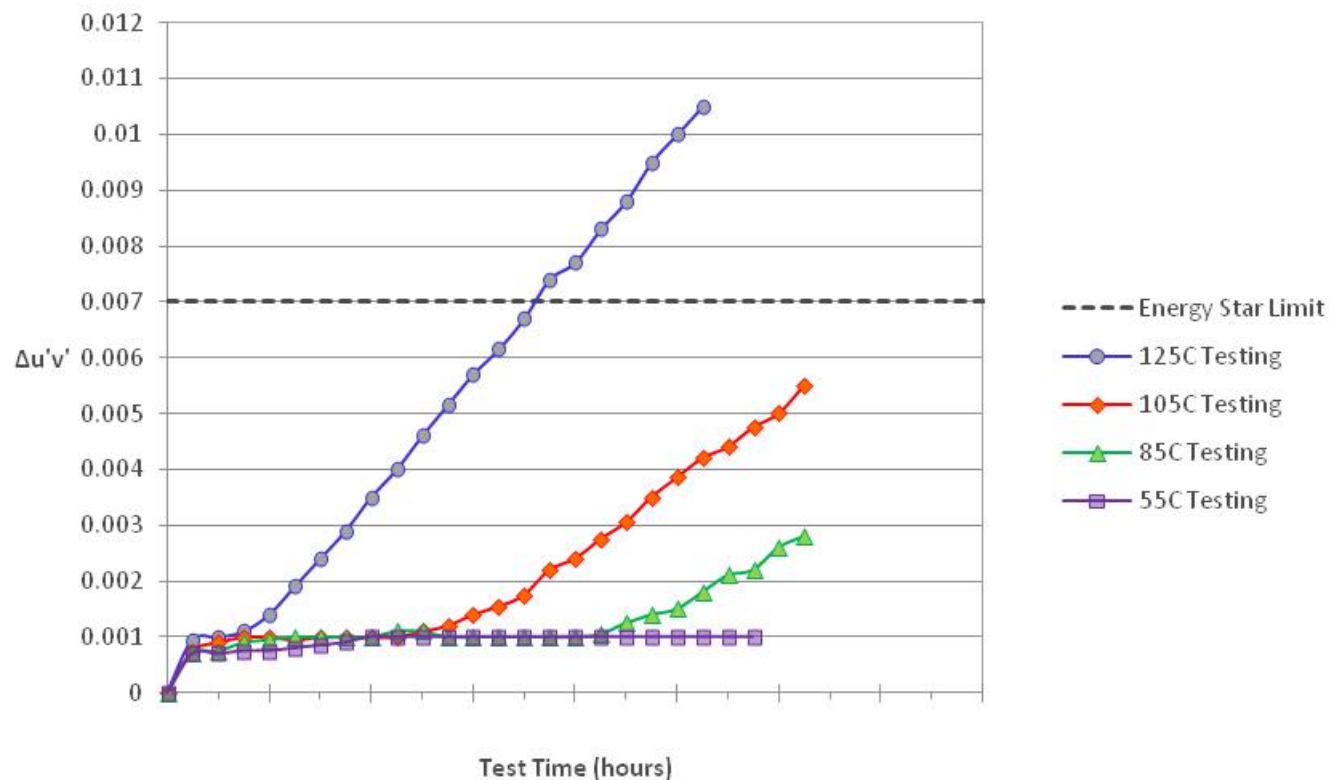
LM-80 testing has also been performed on LED packages at 120° C to 125° C.

Many LEDs DO NOT like operating at 125° C.

Can we use this 125° C testing to accelerate color shift??

8. Projecting Color Shift – LED packages?

High temperature LM-80 testing of LED packages may be useful in accelerating color shift.



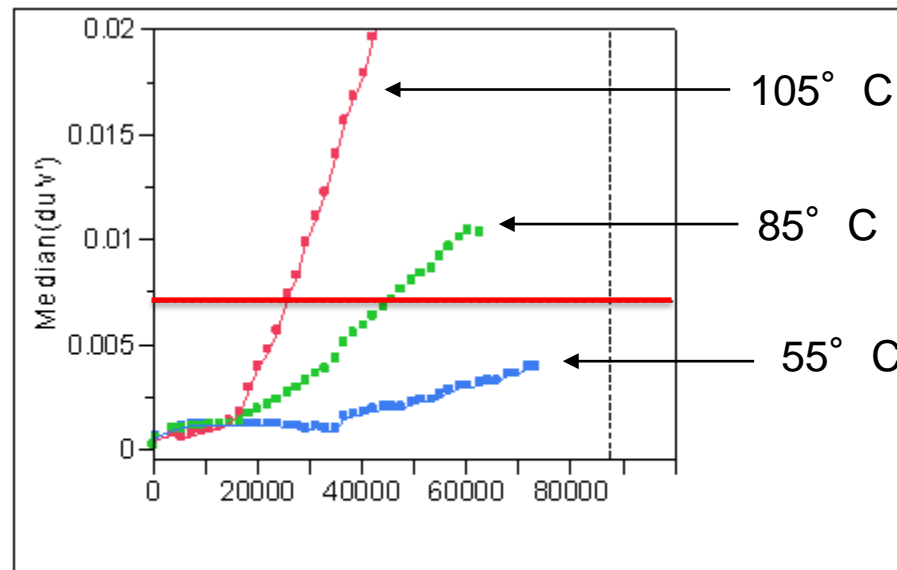
All LEDs are the same chromaticity and operated at the same current.

8. Projecting Color Shift – LED packages?

Can we develop an algorithm that will allow us to project lumen maintenance in time (a la TM-21)?

IES has approve a PIF (Project Initiation Form) to develop such a method...

LED manufacturers are encouraged to provide test data to help the industry develop accurate projecting methods!



/ and operated at the same current.

8. Projecting Color Shift – Luminaires?

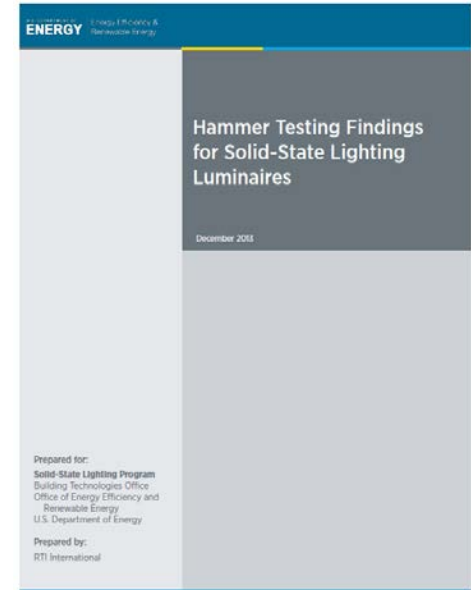
Research Triangle Institute (RTI) has been working on developing a “Hammer Test” to evaluate SSL Luminaire reliability.

A four step luminaire test has been devised which involves a sequence of

- 85%RH/85° C Wet High Temperature Operating Life (WHTOL)
- 50° C to +125° C Thermal Shock (TS)
- 85%RH/85° C Wet High Temperature Operating Life (WHTOL)
- 120° C High Temp Operating Life Test (HTOL)

RTI has been able to cause color point shift in luminaires during WHTOL testing.

Can it be used to actually predict luminaire performance??



9. Are warranties that cover color shift available?

- **Device level warranties are often available**
 - Short term (1 to 3 year)
 - Performance relative to component spec
 - Workmanship
- **Many common end-product warranties are based only on lumen maintenance**
 - L_{70} at 25,000 hours, L_{70} for 5 years (for example)
- **Some warranties offer broader coverage**
 - Lumen maintenance and color stability
 - Relative to balance of installation
 - Based on owners perception

9. Are warranties that cover color shift available?

- **It's not always so straightforward...**
 - Often, the chip manufacturer is different from the lamp or luminaire manufacturer
 - What is allowable?
 - Warranty relative to starting point
 - Warranty relative to other lamps with the same hours of use
 - How many hours/years should be covered?
 - Standardized projections from measured data are not available
 - 6,000 hours is a minimum, but likely not enough
 - What are the procedures for documenting color shift exceeding tolerance?
- **Color Consistency Over Time is more easily documented/covered by warranty**
 - Allows that color shift may occur, but covers that all products will shift together and stay within a specified tolerance
 - What happens in a mixed installation?
- **Warranties may be developed on a case-by-case basis**

10. How should end users and/or specifiers monitor color over time?

- **Establish importance of color shift and review manufacturer data**
- **Is a color shift warranty an option?**
- **What action can be taken if color shift is detected?**
 - Correction?
 - Replacement?
- **Establish a baseline**
 - LM-79 photometry, handheld meter, or product data
 - Accuracy likely restricted by budget constraints
 - Store extra samples of new products?
- **Create a plan for continued monitoring**
 - Visual analysis
 - Handheld metering
 - LM-79 photometry
 - What is the repeatability of measurements?

10. How should end users and/or specifiers monitor color over time?

- **Example 1:**

- Cooperation between Lighting Designer, ESCO, and Manufacturer's Representative
- Regular testing/validation
- Luminaire manufacturer may put funds in bond
 - As time passes and installation passes criteria, funds are refunded or held as appropriate

- **Example 2:**

- Additional product installed off site, run under similar conditions
 - Forms a baseline that is monitored for conformance to spec
 - Held in reserve to be used as replacement product

Conclusions

1. Why and where is color stability important?

LEDs shouldn't be relegated to applications where (standard) metal halide is acceptable. Most indoor applications require good color stability, some require great color stability.

2. What metrics are used to describe color shift/color stability?

For light sources, $\Delta u'v'$ is the best metric for communicating color shift.

3. When does color shift become noticeable?

It depends on the application. A $\Delta u'v'$ of 0.003 may be noticeable for two lights aimed at a white wall, but a $\Delta u'v'$ of 0.007 may be fine in some applications. Proximity and time are key factors.

4. Are there established tolerances for color shift?

ENERGY STAR requires that qualified lamps have a $\Delta u'v'$ of less than 0.007 over the first 6,000 hours. Other than that, no standard tolerances exist.

5. What standards apply to the measurement of color shift?

IES LM-80 (LED packages) is the only standard that truly applies to color shift over time.

Conclusions

6. To what types of products do color stability measurement standards apply?

LM-80 applies to LED packages. Extrapolating those measurements to lamps and luminaires is requires careful consideration.

7. What causes color shift?

LED package materials, luminaire materials, and application-specific factors.

8. Are there methods and/or standards for projecting color shift in the future using measured data?

IES has approved the development of a technical memorandum to project LED package color shift. Recent testing by RTI may allow a similar projection for luminaires.

9. Are warranties that cover color shift available?

Few, true color stability warranties are currently available. There are many factors that make this difficult.

10. How should end users and/or specifiers monitor color over time?

If color stability is a concern and actionable, a proactive approach is necessary.